Surface Water and Ocean Topography Science Team Meeting

Annette deCharon, ODYSEA LLC, avdecharon@gmail.com
Carla Lauter, ODYSEA LLC, carlajean@gmail.com

Introduction

The Surface Water and Ocean Topography (SWOT) mission brings together two international communities whose focus is on better understanding Earth's ocean and surface waters and the interplay between them. U.S. and French oceanographers and hydrologists and other international partners have joined forces to develop this new space-based mission to make the first global survey of Earth's surface water, observe the fine details of the ocean's surface topography, and measure how the height of water bodies change over time.

The first SWOT Science Team Meeting was held in Pasadena, CA, June 13-15, 2016. The meeting was immediately followed on June 16 by parallel sessions of the SWOT Ocean Calibration/Validation Workshop and Hydrology High-Level Data Products Workshop.

SWOT was identified as a "Tier 2" mission in the National Research Council's 2007 Earth Science Decadal Survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*[1], which provided the basis for the future direction of NASA's space-based Earth observation system. SWOT is now scheduled for launch in 2020.

The primary objectives of the SWOT Science Team Meeting were to:

- describe the SWOT mission, its organization, status, and anticipated products;
- introduce the science investigation teams, grouped by synergistic efforts; and
- plan future activity within working groups focused on hydrology, oceanography, and interdisciplinary topics.

The meeting lasted three days to accommodate the contributions of 153 participants across 85 oral presentations, and over 50 posters. A summary, along with all of the presentations from the plenary, splinter, and poster sessions, are available on the SWOT website at *http://swot.jpl.nasa.gov*.

Opening Session

Eric Lindstrom [NASA Headquarters—*Physical Oceanography Program Scientist*] opened the meeting with a status overview of SWOT. He welcomed the new SWOT Science Team members and encouraged them to "grow the SWOT community" through research activities and discussion.

Parag Vaze [NASA/Jet Propulsion Laboratory (JPL)—*SWOT Project Manager*] summarized changes associated with the transition from mission Phase B ("preliminary design") to Phase C ("final design and fabrication"). Together, Lindstrom and Vaze emphasized the importance of ongoing science team involvement as the project strives to maximize science return while balancing mission risk.

Mission Description Session

Presenters in this session shared detailed descriptions of the planned science payload, orbit configuration, data processing, calibration/validation (cal/val) plan, data simulators, and applications.

The SWOT mission is being jointly developed by NASA and the Centre National d'Études Spatiales (CNES) with contributions from the Canadian Space Agency (CSA) and United Kingdom Space Agency (UKSA). **Image credit:** NASA/JPL

Brian Pollard [JPL] provided an overview of the SWOT payload, which is driven by the need for interferometric precision, stability, and continuous data coverage—see **Figure 1**. He provided an overview and status update on the K_a-band Radar Interferometer (KaRIn), nadir altimeter, cross-track Advanced Microwave Radiometer, X-band telecommunications, and instruments for orbit determination—e.g., Détermination d'Orbite et Radiopositionnement Intégré par Satellite (DORIS). Pollard stated that the SWOT payload team has made progress in developing engineering model hardware and expects to have a prototype by the end of 2016.

[1] The report can be downloaded from *www.nap.edu/catalog/11820/earth-science-and-applications-from-space-nationalimperatives-for-the.*

Lee-Lueng Fu [JPL—*SWOT Oceanography Science Lead and Project Scientist*] addressed SWOT's mission design, including differences between the post-launch *fast sampling* orbit and subsequent *science-data-collection orbit*—see **Figure 2**. He stated that during the one-day repeat phase, about three months will be spent focusing on achieving cal/val objectives and studying rapidly changing phenomena. The subsequent 21-day repeat orbit (nominally lasting three years) has been chosen to balance global coverage and frequent sampling. SWOT's orbit, with an inclination between 74° and 80°, will be non-sun-synchronous to minimize tidal aliasing and ensure coverage of major water bodies on land. SWOT's 120-km-wide (~75-mi-wide) swath will result in overlapping measurements over most of the globe, with an average revisit time of 11 days.

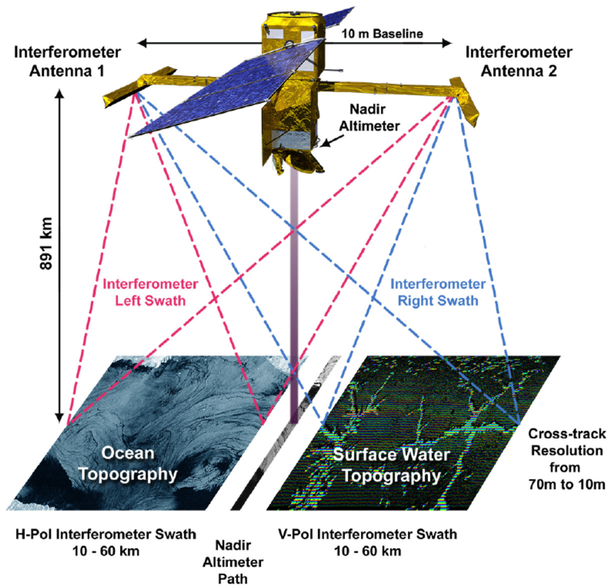

Figure 1. SWOT's K_a-band Radar Interferometer (KaRIn) will have two swaths to determine ocean and surface water topography. A Jason-class altimeter beam will be located between these swaths. **Image credit:** NASA/JPL

The next few presentations described SWOT data processing issues. **Sylvain Biancamaria** [Centre National de la Recherche Scientifique/Laboratoire d'**É**tudes en Géophysique et Océanographie Spatiales (CNRS/LEGOS), France] summarized how SWOT's data High Rate (HR) mode, 10-60 m (~33-197 ft) in range by 5 m (16 ft) in azimuth, cannot sample all continental surfaces because of onboard storage capacity. As a result, the SWOT Science Definition Team formed a working group to define a HR land mask[2] compliant with mission constraints. The HR mask covers 86% of continental surfaces between 78° N and 78° S latitude—excluding Antarctica. **Eva Peral** [JPL] described SWOT's highly flexible onboard processing approach, including individual objectives for each of the algorithms (ocean, land, calibration, and Doppler centroid estimation) that KaRIn will perform. **Daniel Esteban-Fernandez** [JPL] presented SWOT's measurement performance studies, which demonstrate that the system meets mission requirements with an adequate level of margin. He noted, however, that efforts to advance understanding of key phenomenology will continue, and will include examining available datasets, modeling, and simulation efforts.

Phil Callahan [JPL] gave an overview of how JPL, Centre National d'Études Spatiales (CNES; the French Space Agency), and the SWOT Science Team are jointly defining the content of science data products, developing algorithms and their theoretical bases, providing working code and test cases, developing or gathering auxiliary data [e.g., digital elevation models (DEMs)], and supporting independent reviews of algorithms. Callahan outlined key science data products for public distribution, including Low Rate (LR) mode ocean interferograms [average resolution of 500 m^2 (5382 ft^2)] and HR single-look complex radar hydrology products.

Roger Fjørtoft [CNES] gave a complementary presentation to Callahan's, providing details on how raw (i.e., Level-0) synthetic aperture radar (SAR) data from KaRIN will be processed into sets of Level-1 interferograms (i.e., amplitude, phase, coherence). Fjørtoft explained that LR-mode data will be processed onboard the spacecraft while HR-mode data will be downloaded and processed

[2] The SWOT HR mask can be accessed at *http://west.rssoffice.com/SWOT/hrmask.jsp*.

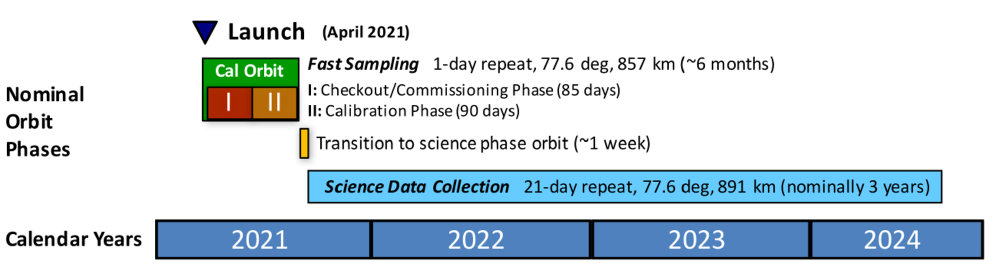

Figure 2. After SWOT's launch (currently scheduled for 2021), there will be an initial *checkout/commissioning phase* lasting about 85 days, followed by a roughly 3-month *calibration phase*. During these initial phases, the mission conducts *fast sampling*, meaning that it will operate on a one-day repeat cycle and focus on achieving cal/val objectives and studying rapidly changing phenomena. Once these two phases are complete (approximately six months after launch) the satellite will be moved to a slightly higher altitude where it will stay for the remainder of the mission (nominally three years). It will take about a week to transition SWOT to *science data collection phase*; data collection will occur on a 21-day repeat cycle designed to balance global coverage and frequent sampling. **Image credit:** NASA/JPL

on the ground. SWOT data will undergo a series of corrections—such as amplitude, signal-to-noise ratio, phase bias, tropospheric delay, and ionospheric and tidal effects. Geophysical factors, including significant wave height, wind, rain, ice, electromagnetic bias, and the potential for *layover*[3] must be estimated and/or flagged.

Ernesto Rodriguez [JPL] presented SWOT's cal/val approach. He stated that a relatively small number (10 – 20) of "Tier 1" sites will be designated as the focus of project-funded cal/val activities for hydrology, augmented by approximately 100 "Tier 2" sites to characterize SWOT spatial variability (e.g., U.S. Geological Survey water level gauges). All Tier 1 sites for hydrology are currently located in North America and France. An existing instrument site in the Gulf Stream will be used for oceanographic validation; this location will be covered by SWOT-orbit crossovers during the fast sampling orbit phase described earlier. Rodriguez pointed out that ocean calibration of sea surface height (SSH) is a major challenge; however, three approaches have been identified to validate the high-frequency spectrum over the ocean: AirSWOT[4], Modular Aerial Sensing System lidar, and *in situ* instrumentation (e.g., moorings, drifters, gliders).

Clement Ubelmann [Collecte Localisation Satellites (CLS), France] and **Ernesto Rodriguez** provided an overview of SWOT's ocean and hydrology simulators, respectively. Ubelmann explained that the ocean simulator was developed in collaboration with SWOT's Science Definition Team and was principally designed for scientists to investigate SWOT downstream applications using realistic data. Available online[5], it relies on spectral-error budget specifications and has been used to explore various science applications for SWOT. The *SWOT Hydrology Simulator* generates radar interferograms, detects pixels that represent water, and geolocates to a pixel cloud. It is accompanied by *RiverObs*, which takes in the pixel-cloud output from the *SWOT Hydrology Simulator* to estimate key parameters (e.g., width, height, slope) over river segments.

Margaret Srinivasan [JPL] concluded the session with an overview of SWOT's applications efforts, which are being implemented at the project level with support from NASA, CNES, and the Science Team. She explained that the SWOT Applications Working Group (SAWG) provides feedback on data-product development with respect to applications (and vice versa) and helps to disseminate information about SWOT applications-relevant data to broad communities. Srinivasan stated that SAWG team members have authored key documents (e.g., the *SWOT Applications Plan, Applications Traceability Matrix,* and various journal articles), administered a user needs survey, and implemented an "Early Adopters" program for stakeholders who can demonstrate the utility and/or social value of SWOT data using resources obtained outside of NASA's Applications programs.

Highlights from Science Team Topical Area Presentations

To kick off the meeting's second day, members of the SWOT Science Team gave presentations grouped by topic; lead presenters provided a high-level summary of the group's collective work. These introductions oriented the audience to the posters being presented that afternoon, many of which can be accessed online at *http://swot.oceansciences.org/meetings_posters.htm*. Each of the topics listed below encompasses the work of several investigators. One presenter represented the work of all the investigators in each topical area.

Oceanography topical areas included:

Meso- and Sub-Mesoscale Processes and Modeling: Projects will employ a range of inversion techniques of varying complexity to infer lateral and vertical exchanges from SWOT data.

Meso- and Sub-Mesoscale Processes and Observation System Simulation Experiments: Projects will use model and *in situ* data to demonstrate SWOT's potential contributions to understanding links among ocean physics, biogeochemistry, and ecology.

Techniques for Reconstruction and Assimilation of SWOT Ocean Observations: Projects will use data from multiple sources (e.g., sea surface temperature, nadir altimetry, elephant seals equipped with temperature and salinity sensors) in conjunction with dynamics to determine ocean state with the longer-term goal of informing how to process gridded SWOT map fields.

Tides, Waves, and High-frequency Processes: Projects will support the SWOT mission by developing tide models (i.e., barotropic, baroclinic), modeling internal wave signals and their predictability, and characterizing global internal tides at high horizontal resolution.

SWOT Oceanography Cal/Val: The overall goal of these projects is to establish a network of calibration sites geographically distributed for more robust characterization of existing and future radar altimeter system instrument biases and their drifts over ocean and inland waters. In addition, the group is involved in developing high-resolution models (i.e., tides, dynamic atmospheric correction).

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[3] *Layover* in SAR data occurs when, due to topography or vegetation, returns from separate areas on the ground reach the sensor at the same time.

[4] AirSWOT is the airborne cal/val and science support instrument for the SWOT mission. To learn more, visit *http://swot.jpl.nasa.gov/airswot*.

[5] The open-source SWOT Simulator for Ocean Science can be accessed at *http://sourceforge.net/projects/swotsimulatorfor-oceanscience*.

Coastal and Estuarine Processes: These projects will augment previous studies that demonstrated SWOT's ability to reproduce coastal hydrodynamics across a broader range of environments with different tidal contexts (i.e., macro-, meso-, and micro-tidal), diverse morphologies (i.e., estuary, delta, bay, sandy beach, cliff, and shelf), and in various climates (i.e., temperate, Mediterranean, tropical, and Arctic).

Hydrology topical areas included:

Global Hydrologic Modeling: These global-scale efforts will interact through a multiyear, multiphase, intercomparison project with shared methodology development, providing a multimodel vision of global hydrologic processes and potential SWOT impact.

River Algorithms, Models, and Data Assimilation: Projects include developing global assimilation and modeling frameworks for SWOT data products, river and assimilation-based discharge algorithms, hydrologic and hydrodynamic modeling in South America, and synergies between SWOT and the Global Precipitation Measurement (GPM) mission.

Lake, River, and Wetland Processes and Science: These projects, whose study sites span six continents, generally use radar altimeter data to characterize water surface extents while addressing lake, river, and wetland dynamics.

SWOT Hydrology Cal/Val: Projects are largely focused on validation during the fast sampling (i.e., one-day repeat) phase of the mission, studying hydrologic parameters and phenomenology in North and South America.

Synergistic Science: These diverse projects will use SWOT data to improve the resolution and accuracy of the global marine gravity field for seafloor mapping and tectonic investigations; understand polar ice sheet dynamics; monitor ice-covered polar oceans in terms of SSH, sea ice freeboard, and thickness; and a United Kingdom-based effort focused on open-ocean and coastal oceanography, along with sea-ice and atmospheric effects on instrument performance.

Applications: Wide-ranging projects include performing outreach to open broad access to information about the SWOT mission and its applications; integrating lateral contributions and longitudinal controls along river segments to improve discharge estimates for flood hazards, risks, insurance, etc.; and preparing SWOT for "ground-truthing," discharge product development, and water-management applications in Asian river systems.

Themes and Challenges for SWOT

After (and as a result of) the second day's presentations and deliberations, Science Team members summarized key themes and challenges for SWOT moving forward. They are listed here by topical area, or theme:

Oceanography Challenges

- Understanding the two-dimensional SSH signal;
- analyzing high-frequency dynamics for SWOT (i.e., tides, internal waves, surface waves);
- characterizing coastal zones (including estuaries and deltas);
- understanding the two-dimensional SSH error budget over the SWOT swath;
- projecting fine-scale SWOT observations horizontally and vertically; and
- developing data products and applications.

Hydrology Challenges

- Improving stand-alone SWOT discharge algorithms;
- developing and testing robust, global assimilation schemes in hydrologic and hydrodynamic models;
- developing more datasets to test algorithms (e.g., models, simulator, AirSWOT);
- identifying optimal ways to leverage existing *in situ* and satellite datasets to improve SWOT discharge estimates;
- figuring out how to robustly estimate and incorporate layover;
- developing robust global models and assimilation schemes;
- assessing how assimilation of SWOT data will improve water-cycle representation;
- developing assimilation schemes to leverage SWOT data in one- and two-dimensional hydrodynamic models; and
- applying model results to improve SWOT algorithms.

Highlights from the Working Group Reports

The last day of the SWOT Science Team Meeting began with reports from working groups and other teams. These Working Group reports set the stage for issues to be discussed in more detail during the subsequent splinter sessions.

Ernesto Rodriguez discussed the structure of the Algorithm Team, key areas of concern, and the need to broaden the representation of science team members and disciplines on the algorithm team (e.g., sea ice, continental ice sheets, ocean bathymetry/gravity). He followed with a report from the Cal/Val Steering group outlining the team's organization, workflow, and "hot topics" (e.g., mix of airborne and *in situ* data, integration of efforts among cal/val sites, pre-launch activities).

Richard Ray [NASA's Goddard Space Flight Center] represented the Tides Working Group. He stated that the group's focus is on assessing the accuracy of coherent internal tide models and correcting/flagging incoherent internal tides. They are also developing an atlas for local high-resolution models for barotropic tides in coastal and shallow sea areas, along with improving tidal models at high latitudes.

Patrice Klein [Institut français de recherche pour l'exploitation de la mer (Ifremer)] presented results from three years of analysis of high-resolution [1-4 km (0.6-2.5 mi)] ocean general circulation models. This effort has revealed some new impacts of small-scale phenomena [10-50 km (~6-31 mi)] at larger scales, leading to two specific recommendations: revisit existing satellite and *in situ* data to confirm new results; and continue to increase simulation resolution.

Colin Gleason [University of Massachusetts Amherst] described the activities of the Discharge Algorithm Working Group (DAWG), which is tasked with generating river discharge estimations from SWOT measurements. The DAWG's principle activity, also known as the *Pepsi Challenge*, is testing discharge results from different inversion algorithms, all of which use the same assumptions and 19-river hydraulic model dataset (width, height, slope).

Margaret Srinivasan concluded the plenary session with a report from the SWOT Applications Working Group including key publications, presentations, and SWOT Applications user needs survey results. She also discussed broad issues related to funding, interactions with operational agencies, participation of private industries, and synergies with other NASA missions.

Splinter Sessions

The majority of day three was spent in splinter sessions. **Rosemary Morrow** [CNRS/LEGOS] and **Lee-Lueng Fu** [JPL] chaired the Oceanography session, while **Tamlin Pavelsky** [University of North Carolina (UNC)] and **Jean-Francois Cretaux** [CNRS/LEGOS] both chaired the Hydrology splinter session.

Oceanography

The oceanography splinter session began with presentations related to the effects of various ocean phenomena on SSH signals at length scales of 15-150 km (9-93 mi). **Raffaele Ferrari** [Massachusetts Institute of Technology], **Brian Arbic** [University of Michigan, and **Edward Zaron** [Portland State University] focused on the effects of internal waves, internal tides, gravity waves, and nonstationary tides on SSH signals.

The next series of presentations addressed the effects of surface waves on SSH signals, during which **Ernesto Rodriguez** and **Ken Melville** [Scripps Institution of Oceanography] discussed AirSWOT and airborne lidar measurements, pointing out the utility of these intercomparisons for SWOT science and cal/val activities. **Fabrice Ardhuin** [Ifremer] gave an overview of the effects of surface waves on SSH based on theories and models (e.g., sea-state biases caused by uneven power returns from horizontal facets at the surface).

The next focus was on estimates of upper-ocean circulation, where **Clement Ubelmann** [CLS], **Dudley Chelton** [Oregon State University], **Bo Qiu** [University of Hawaii at Manoa], and **Jim McWilliams** [University of California, Los Angeles] presented their work, which ranged from exploration of dynamic interpolation methods, estimation of surface velocity and vorticity based on data at SWOT resolution and reconstruction of vertical velocities in the ocean, to addressing the limits of geostrophic dynamics at the ocean surface at various scales.

Nathalie Steunou [CNES] concluded the session with a report on SWOT's LR Level-2 (gridded, mapped) data products. She outlined the steps that will be taken to convert nine beam interferograms to 1 km^2 (0.4 mi^2) SSH products. She reviewed the origin and geometry of the KaRIn beams: 9 beams, spread out in the along-track direction, which yield 9 separate images [500 m x 500 m (1640 ft x 1640 ft) pixels] that are shifted by approximately 200 m (~656 ft) each. This results in center beams being more reliable and thus weighted higher during processing—see **Figure 3**. She provided a table of SWOT's Level-2 products, along with information on the expected LR data volume (per day and per half-orbit) for various product types.

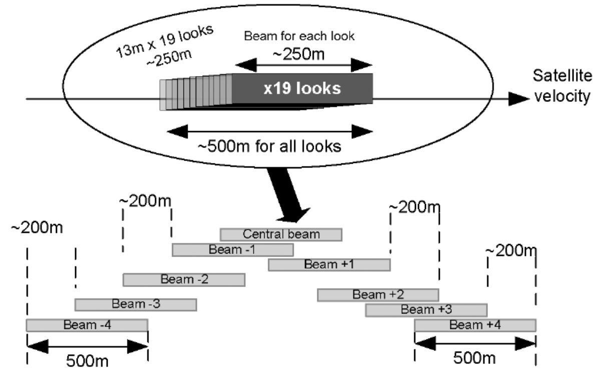

Figure 3. Diagram of the KaRIN beam configuration.
Image credit: CNES, NASA/JPL

Hydrology

The Hydrology splinter session opened with a simulator tutorial by **Brent Williams** [JPL] featuring two primary packages: *SWOT Hydrology Simulator* and *RiverObs*. The *SWOT Hydrology Simulator* directly generates interferograms with appropriate statistics for SWOT geometry. *RiverObs* is a proof-of-concept vector product that reads *SWOT Hydrology Simulator* data.

Tamlin Pavelsky [UNC] then provided an overview of AirSWOT and data from its hydrology campaigns (e.g., Willamette River, OR; Sacramento River, CA; Wax Lake Delta, LA; Tanana River, AK). While there have been good results in measuring river height and slope, preliminary findings generally demonstrate the need for future work such as collecting additional data, addressing errors, and reprocessing some existing data.

Pierre-André Garambois [Institut National des Sciences Appliquées (ICube)] then addressed how best to use SWOT data to infer river discharge at the global scale and provided an overview of data from DAWG's *Pepsi Challenge*, as described earlier in this article. This topic prompted a group discussion about organizing SWOT model intercomparisons for data assimilation purposes.

Stéphane Calmant [LEGOS] shared the benefits of leveraging international partnerships such as engagement in SWOT cal/val. He outlined specific activities that have already begun with partners in South America (i.e., Brazil, Chile, Paraguay, Uruguay). **Alain Pietroniro** [Environment Canada] provided background on activities in Canada including identification of potential river-based SWOT cal/val sites and plans to use SWOT hydrology simulators.

The Hydrology Splinter Session ended with the discussion of several interesting potential appplications for SWOT data.

Brent Williams [JPL] addressed the use of SWOT interferograms for land-based water detection. **Jean-Francois Cretaux** [CNRS/LEGOS] noted the need for a prelaunch *a priori* focused on lakes database. **Renato Frasson** [Ohio State University] using SWOT data to establish *reach boundaries* for features such as tributaries, confluences, dams, and waterfalls. **Clement Ubelmann** [CLS] discussed using SWOT's ocean coverage—especially at swath cross-over points—and inland interpolation to correct hydrology measurements.

Closing Session

The meeting concluded with two science presentations and summaries of future plans from the oceanography and hydrology leads.

Benoit Laignel [University of Rouen] addressed issues and questions in coastal-estuary-river continuums, areas that are significantly impacted by human activity and climate change. SWOT's high spatial resolution and global coverage could be used to improve knowledge of the complexity of physical processes (e.g., floods, tides, storm surges) and its data could help calibrate and validate models. He suggested investigating how SWOT science products could be designed to meet the needs of stakeholders in these regions.

Jerome Monnier [L'Institut National des Sciences Appliquées de Toulouse] reported on the potential for SWOT to contribute to the understanding of polar ice sheet dynamics and a fully integrated data assimilation system. For example, data from SWOT may be helpful for measuring *grounding lines*—where ice sheets contact the ocean and the ice mass starts to float by buoyancy—or inferring bed topography beneath ice caps, ice flows, and other related phenomena.

Tamlin Pavelsky [UNC] summed up the key points from the Hydrology presentations and discussions, including the desirability of establishing continental hydrologic model and geoid working groups, along with increased involvement of Science Team members with SWOT algorithm development and cal/val efforts. He also mentioned ongoing analyses of AirSWOT data and future development of mapped, gridded, and model output products.

Lee-Lueng Fu [JPL] provided a summary of the Oceanography session, including the formation of working groups for surface waves, tides/internal waves, HR modeling, reconstruction (i.e., handling geostrophic and ageostrophic SSH components and errors), and coastal/estuarine studies. He mentioned upcoming meetings and the development of a "Mission Science Investigation Plan," which will include summaries from each investigation team.

Conclusion

The meeting fulfilled all its objectives. It provided a forum for new Science Team members to become familiar with the SWOT mission and each other's work. The meeting set the stage for important tasks to be completed during Phase C of the mission. The top priorities include completing the plans for the mission's calibration and validation and the development of science algorithms. In hydrology, the key objectives are to develop river discharge models, characterize the effects of layover, and wetland data product definition. The key oceanographic objectives include understanding the effects of internal gravity waves and surface gravity waves on sea surface height observations, developing tide models, and using high-resolution ocean models to develop science investigation plans. Various working groups have been formed to address these priority tasks. The next SWOT Science Team meeting will take place during June 2017 in France. ■